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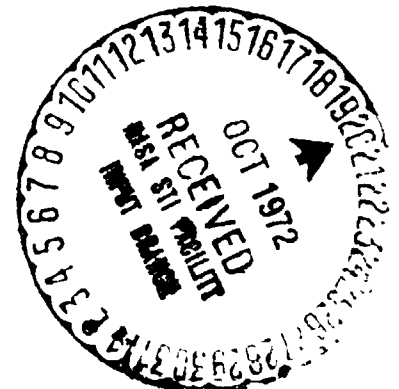
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**ESTIMATION OF SEA SURFACE
TEMPERATURE FROM REMOTE
MEASUREMENTS IN THE
11-13 μ m WINDOW REGION**

**C. PRABHAKARA
B. J. CONRATH
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FROM REMOTE MEASUREMENTS
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by

C. Prabhakara, B. J. Conrath, V. G. Kunde

Goddard Space Flight Center

Greenbelt, Maryland 20771

ABSTRACT

The Nimbus-4 IRIS data is examined in the spectral region 775 to 1250 cm^{-1} (8 - $13\text{ }\mu\text{m}$) for useful information to determine the sea surface temperature. The high spectral resolution data of IRIS is degraded to low resolution by averaging to simulate a multi-channel radiometer in the window region. These simulated data show that within the region 775 - 975 cm^{-1} (12.9 - $10.25\text{ }\mu\text{m}$) the brightness temperatures are linearly related to the absorption parameters. Such a linear relationship is observed over cloudy as well as clear regions and over a wide range of latitudes. From this linear relationship it is feasible to correct for the atmospheric attenuation and get the sea surface temperature, accurate to within 1°K , in a cloud free field of view. The information about the cloud cover is taken from the TV pictures and BUV albedo measurements on board the Nimbus-4 satellite.

INTRODUCTION

Sea surface temperature has been estimated by Allison and Kennedy (1967), Smith et al. (1970), Shenk and Solomonson (1972) and others from the measurements of infrared radiation obtained by satellites and a feasibility study has been carried out by Anding and Kauth (1970). A scrutiny of these studies shows that it is necessary to have a cloud free field of view in order to estimate the sea surface temperature from space. Also one has to apply atmospheric attenuation correction to the satellite observations.

Atmospheric attenuation corrections used in previous studies have been done on a climatological basis. It is desirable to make such corrections consistent with the atmospheric conditions prevailing at the time and place. Such a consistent correction could be made using soundings of temperature and humidity. However, the acquisition of such sounding data would demand an elaborate system of measurements. The scheme presented here requires a broad band radiometer with two or three spectral channels in the region $775-975\text{ cm}^{-1}$ region of the window and one channel to measure albedo in the visible radiation, $\sim .5 - .7\text{ }\mu\text{ m}$, to eliminate cloud contaminated data. It is shown that these measurements can be used to correct for atmospheric attenuation without recourse to climatological data.

THEORY

Remote sounding methods are commonly based on differential optical properties of gaseous constituents in the atmosphere. From this point of view

in the estimation of sea surface temperature the differential behavior of the window region should be useful in inferring the atmospheric attenuation. However, to make such an inference the optical properties of the region must be known.

There have been many investigations of water vapor absorption in the window region. Roach and Goody (1958) found that in the window region continuum absorption obeying Lambert's law is much stronger than the selective absorption due to water vapor rotational lines. Bignell (1970) and Burch (1970) find the continuum absorption coefficient in the window region is dependent on the vapor pressure of water. Carlon (1971) contends that water aerosols in the atmosphere have absorption similar to water vapor and hence would produce an apparent enhancement of water vapor window absorption. The absorption due to atmospheric CO_2 in the window region is small compared to that due to water vapor. Recognizing the complexities involved, we have made a simple working model based on the data of Burch (1970) of the absorption properties of the window region. This model essentially emphasizes the continuum absorption character of the water vapor to arrive at 'relative' absorption coefficients for the window region $775\text{--}975\text{ cm}^{-1}$. These relative absorption coefficients permit us to develop an algorithm to correct for the atmospheric attenuation. The adopted values of these coefficients for three spectral regions of the window to be utilized in the subsequent analysis are shown in Table 1.

Table 1

Relative absorption coefficients for the window region. (Based on continuum absorption coefficient measured by Burch 1970, at a temperature of 296°K).

Spectral Interval $\Delta \nu \text{ cm}^{-1}$	Relative Absorption Coefficient $k(\nu)$
775-831	0.465
832-887	0.320
888-975	0.255

The radiative transfer equation may be written as

$$I(\nu) = B[\nu, T(P_0)] \tau(\nu, P_0) + \int_{\tau(\nu, P_0)}^1 B[\nu, T(p)] d\tau(\nu, p) \tag{1}$$

where I is the outgoing intensity of radiation and ν is the wave number; p and T are pressure and temperature in the atmosphere; and p_0 is the surface pressure; B is the planck intensity; and τ is the transmittance. The surface emissivity is assumed to be unity.

The above equation may be simplified as

$$I(\nu) = B[\nu, T(P_0)] \tau(\nu, P_0) + \bar{B}(\nu) [1 - \tau(\nu, P_0)] \tag{2}$$

where $\bar{B}(\nu)$ is the weighted mean Planck emission of the atmosphere.

In the window region, as the absorption is weak, we can approximate the transmission τ as

$$\tau(\nu) = e^{-k(\nu)u} \cong 1 - k(\nu)u \quad (3)$$

where $k(\nu)$ is the absorption coefficient and u is the effective absorber thickness. The exponential form of the transmission function emphasizes the Lambertian type of the water vapor continuum absorption in the window region. But, in general, selective absorption due to water vapor lines also can be approximated to a linear form such as that given by equation (3) when the absorption is weak (Goody, 1964). The same argument is applicable to some weak bands of CO_2 in the window region.

Substituting the approximate form of $\tau(\nu)$ given by equation (3) into (2) we get

$$I(\nu) \cong B[\nu, T(P_0)] - [B(\nu, T(P_0)) - \bar{B}(\nu)] u k(\nu) \quad (4)$$

The planck function B can be expanded about the surface temperature $T(P_0)$ and only the linear term retained to yield

$$B(\nu, T) = B[\nu, T(P_0)] + \frac{\partial B[\nu, T(P_0)]}{\partial T} [T - T(P_0)] \quad (5)$$

This approximation holds good over small range of temperatures and a narrow wave number span. With this approximation equation (4) becomes

$$I(\nu) \cong T(P_0) - [T(P_0) - \bar{T}(\nu)] u k(\nu) \quad (6)$$

where $T(\nu)$ is the brightness temperature, $\bar{T}(\nu)$ is the equivalent radiative temperature of the atmosphere, and $T(P_0)$ is the surface temperature.

Equation (6) indicates a linear relationship between the brightness temperature and the absorption coefficient, provided $\bar{T}(\nu)$ is not strongly dependent on ν . A study by McMillin (1971) shows that \bar{T} is nearly constant in this region. Thus with a minimum of two measurements, the surface temperature $T(P_0)$ can be determined.

IRIS Observations of 8-13 μm Window Region

The Nimbus 4 Infrared Interferometer Spectrometer (IRIS) has obtained spectra in the region $\sim 7\text{--}25 \mu\text{m}$ with a resolution of 2.8 cm^{-1} . IRIS has a field of view of about 95 km and a noise equivalent radiance of $\sim 0.5 \text{ erg cm}^{-1} \text{ sec}^{-1} \text{ ster}^{-1}$. These high quality data are ideally suited to study the behavior of the 8-13 μm window region on a global basis over a wide range of meteorological conditions. IRIS data can be analyzed conveniently in terms of brightness temperatures derived from measured radiance values. In Fig. 1 a selection of IRIS brightness temperature spectra are shown in the region 775 to 1200 cm^{-1} avoiding the $9.6 \mu\text{m}$ ozone band. We find the high resolution data in the $775\text{--}975 \text{ cm}^{-1}$ region show a gradual increase of temperature from low to high wave number. This feature appears in clear as well as cloudy conditions. The spectrum between $1094\text{--}1200 \text{ cm}^{-1}$ lacks this property due to increasing selective absorption by the water vapor lines in the wing of the $6.3 \mu\text{m}$ water vapor band. The

775-975 cm^{-1} region, having less selective absorption, more nearly satisfies the assumption of weak absorption. Thus it is this region that has been utilized in the present study.

The IRIS brightness temperature data in the 775-975 cm^{-1} region are divided into three segments (1) 775-831, (2) 832-887, (3) 888-975 cm^{-1} and the mean brightness temperature for each one of these spectral intervals is computed. By doing so the noise in the IRIS data is reduced and the lines can be smoothed out to simulate measurements of a crude resolution radiometer. The three brightness temperatures obtained in this fashion from IRIS spectra measured at several different oceanic regions are plotted as a function of the relative absorption coefficient $k(\nu)$ as shown in Fig. 2. We find that the three brightness temperatures obey the linear relationship of equation (6) very closely. As we would expect the straight line has a negative slope indicating more absorption when the absorption coefficient increases. The intercept of this straight line on the ordinate, where the absorption is zero, gives the brightness temperature of the surface. In a cloud-free region of the ocean we can determine the sea surface temperature in this manner. The Nimbus 4 BUV albedo measurements (Mateer et al. 1971) and the IDCS pictures have been used to define cloud-free areas on the seas.

While (6) was derived on the basis of weak absorption in the window region, it is found from the IRIS data to hold over a wide range of atmospheric conditions prevailing over the earth's oceans.

Because of the relatively large field of view (95 km) of IRIS most of the data is affected by some cloudiness and hence it has not been possible to make a sea surface temperature map. Further, since the aim of this investigation is to show the feasibility of estimating sea surface temperature from the window measurements, we have made only a limited data analysis.

Sea surface temperatures estimated from the data shown in Fig. 2 have been compared with nearby ship measurements, and the results are shown in Table 2. This limited data analysis indicates that the method presented in this study is capable of retrieving the sea surface temperature to within about 1°K .

In order to illustrate the advantages of estimating the sea surface temperature from the present method we are presenting in Fig. 3 the data obtained from IRIS over a cloud-free region of the Arabian sea. It may be noticed from the figure that the IRIS window brightness temperatures increase by about 3.5°K going from about 8°N to 14°N . With climatological atmospheric attenuation corrections applied to these window measurements one would infer that the sea surface temperature increases towards the north by about the same magnitude. However, with the atmospheric attenuation correction based on the present scheme, the estimated sea surface temperature does not increase toward the north; instead it shows a decrease of about 1°K in agreement with the climatological data (U. S. Naval Oceanographic Office, 1967) for that oceanic region.

Table 2
Nimbus 4 IRIS Sea Surface Temperature Estimation
Vs. Ship Measurements

<u>No.</u>	<u>Date</u>	<u>Lat.</u>	<u>Long.</u>	<u>Temperature</u>	
				<u>IRIS</u>	<u>Ship</u>
1	May 10, 19	11°N	51°W	300.1	
		10.5°N	51°W		300.5
2	May 10, 1970	36.6°N	60.9°W	292.0	
		35.6°N	60.5°W		290.5
3	May 10, 1970	35.8°N	33.8°W	289.6	
		36°N	35°W		291.0
4	May 10, 1970	44.6°N	37.1°W	287.7	
		44°N	41°W		287.0
5	May 10, 1970	41.0°N	62.5°W	281.1	
		41°N	62.5°W		281.0
6	May 10, 1970	19.7°N	82.6°W	300.7	
		20.1°N	82°W		301.5
7	April 27, 1970	15.1°N	144.7°W	300.1	
		Guam Water Temp.			301.2
8	June 25, 1970	39.4	69.1°W	298.0	
		Wallops Island Water Temp.			296.2

Conclusions

The basic result of this study is that over the oceans we can make use of the differential absorption properties of the window region to correct for the atmospheric attenuation. This correction scheme inherently takes into account the temperature and humidity structure prevailing at the location. Although three measurements in the window region $775\text{--}975\text{ cm}^{-1}$ were used to demonstrate this method, in principle two measurements are sufficient. The two window measurements may preferably be in the approximate regions $775\text{--}831$ and $888\text{--}950\text{ cm}^{-1}$ to obtain maximum effect of differential absorption. For an instrument operating in these two spectral intervals the random error in the estimation of the sea surface temperature can be shown to be about 3 times the noise equivalent temperature of the measurements. From this consideration it would be desirable to have a radiometer capable of measuring accurately to 0.1°K .

The scheme presented here can be adopted to any existing sea surface temperature measurement program, based on one window channel, by adding one more channel in the window.

The spatial and temporal changes of sea surface temperature in the tropics are generally small $\sim 2^\circ\text{C}$. The atmospheric attenuation corrections over the tropics could range from $\sim 3^\circ\text{C}$ to 4°C . Hence we should estimate the atmospheric attenuation corrections properly. The technique presented in this study to obtain such correction, is a simplified form of radiative transfer inversion

based on physical principles. This should be preferable to statistical methods of estimating the attenuation correction.

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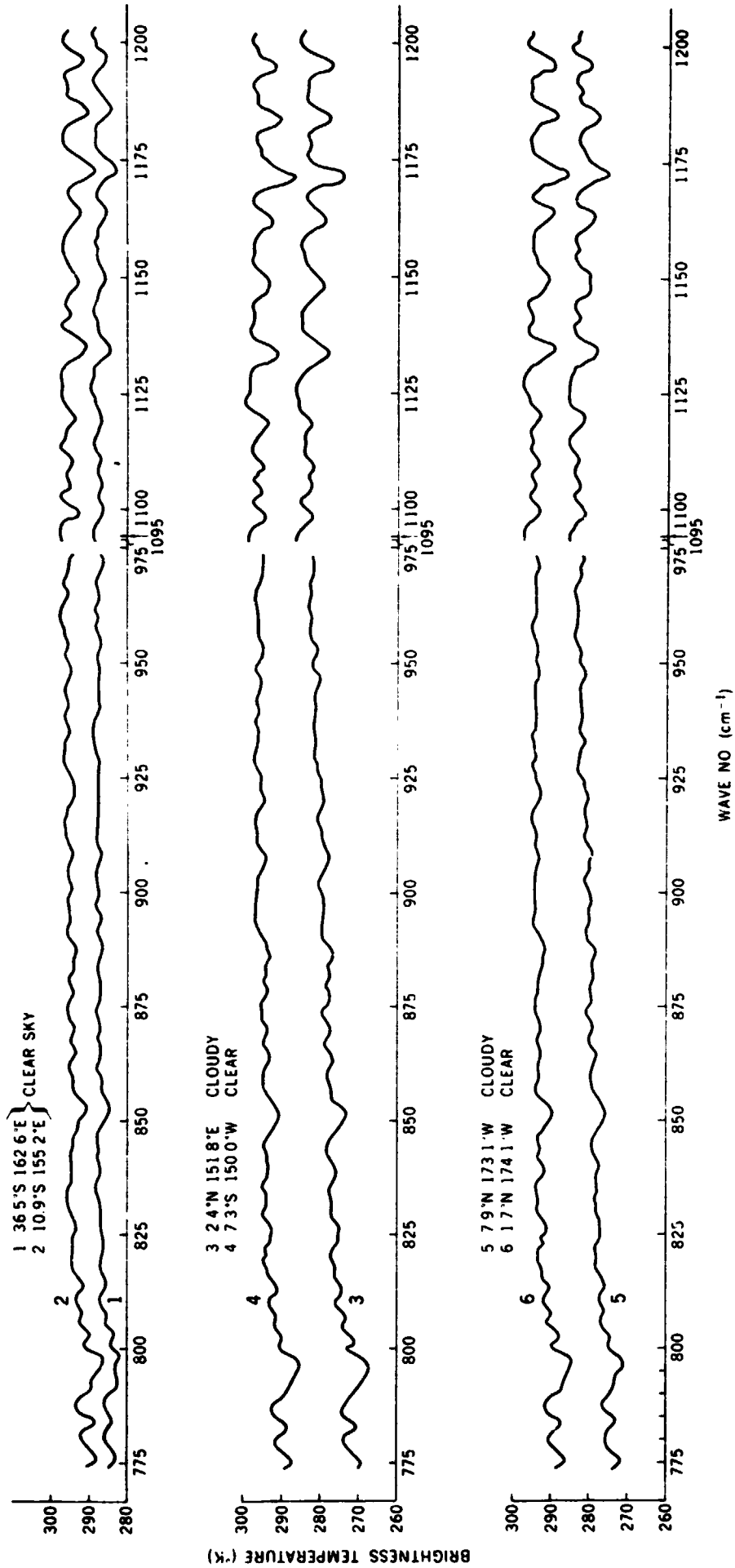


Figure 1. IRIS-4 measured brightness temperature in 8-13 μm window

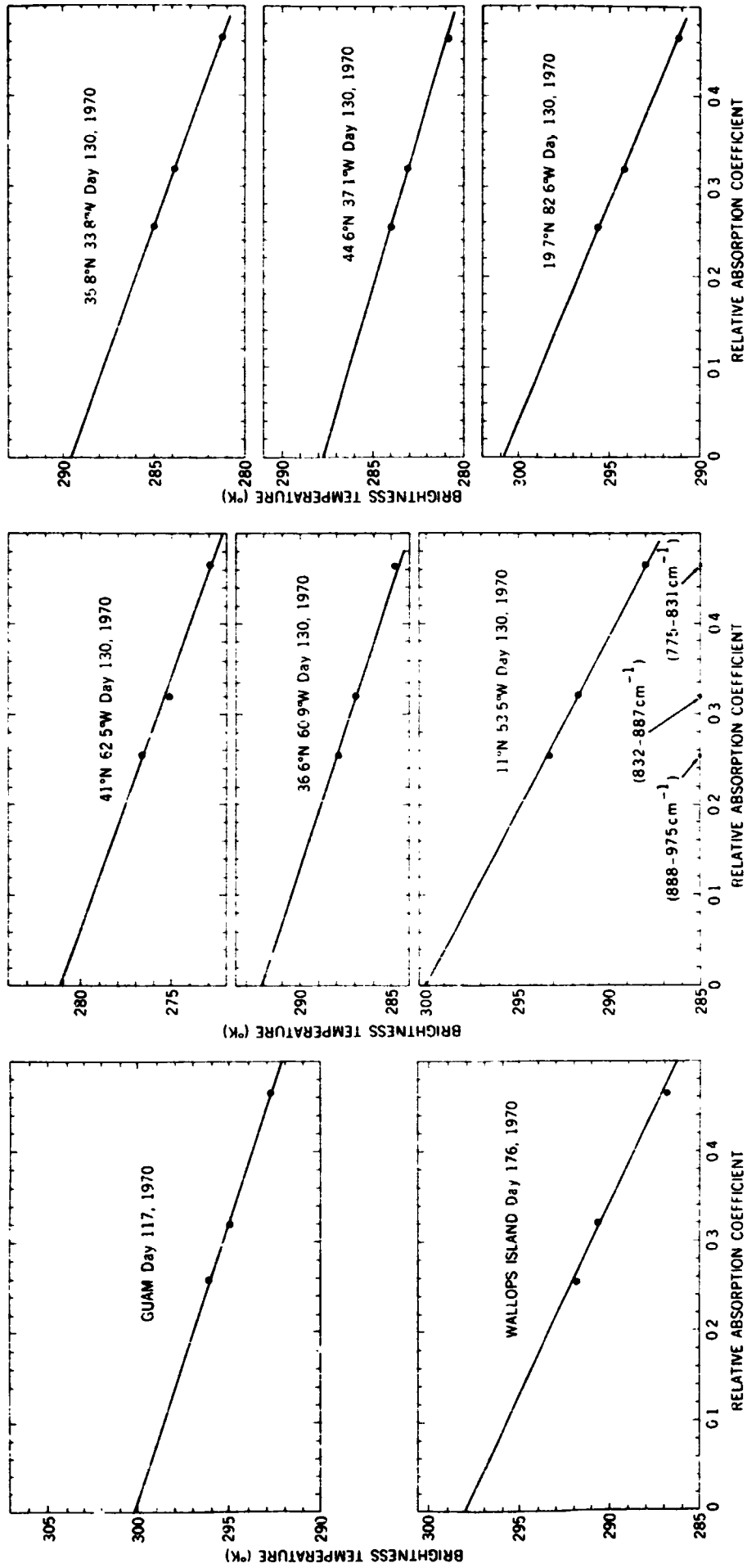


Figure 2. IRIS window brightness temperature vs. relative absorption coefficient

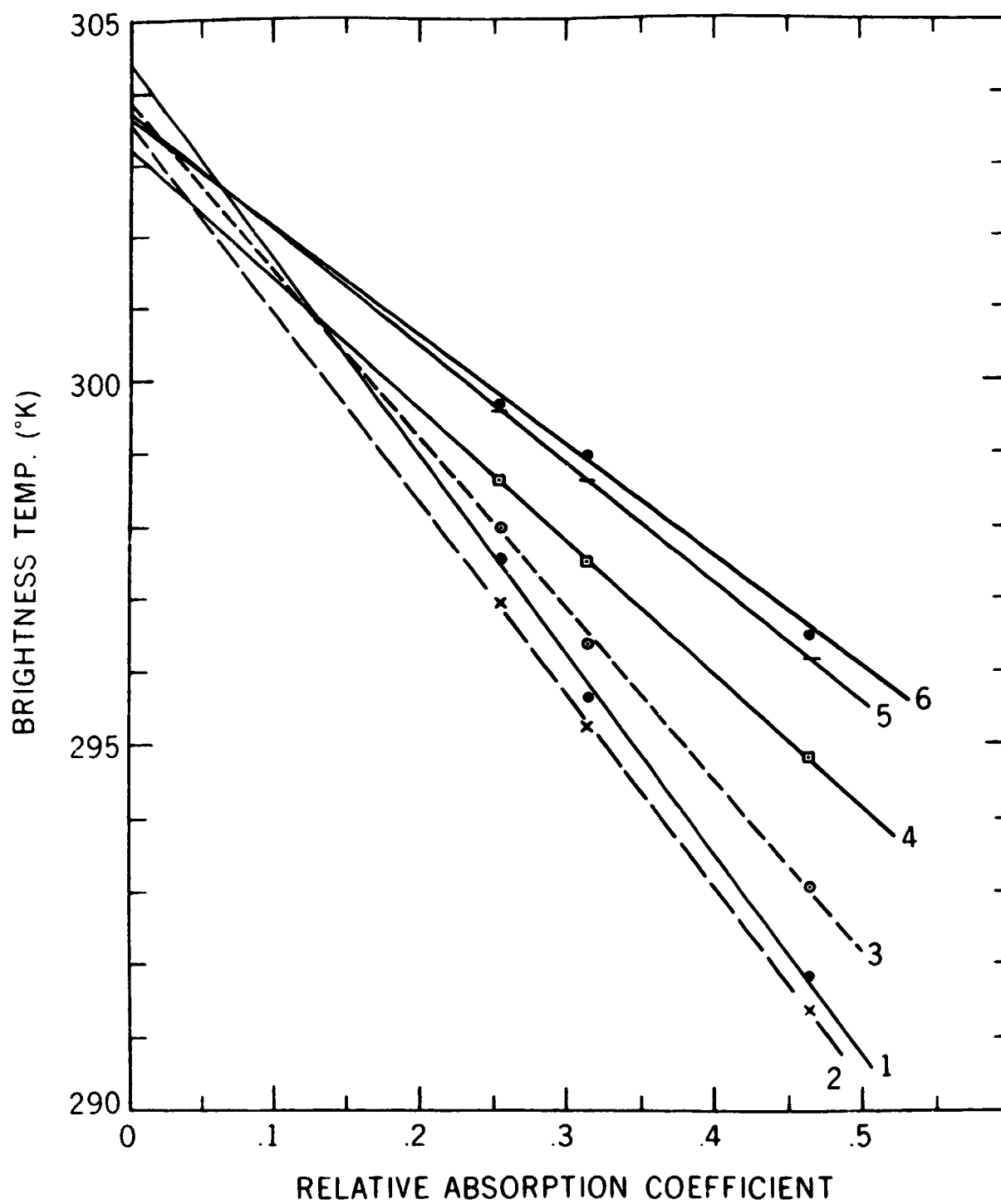


Figure 3. Window brightness temperature variation over the Arabian sea between 8°N (No. 1) to 14°N (No. 6) along 60°E longitude on May 10, 1970